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24 March 2015

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Burt, T.P. and Howden, N.J.K. and McDonnell, J.J. and Jones, J.A. and Hancock, G.R. (2015) 'Seeing the climate through the trees : observing climate and forestry impacts on streamflow using a 60-year record.', Hydrological processes., 29 (3). pp. 473-480.

Further information on publisher's website:

http://dx.doi.org/10.1002/hyp.10406

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HP Scientific Briefing

Seeing the climate through the trees: observing climate and forestry impacts on streamflow using a 60-year record

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Abstract

Paired watershed experiments involving the removal or manipulation of forest cover in one of the watersheds have been conducted for more than a century to quantify the impact of forestry operations on streamflow. Because climate variability is expected to be large, forestry treatment effects would be undetectable without the treatment-control comparison. New understanding of climate variability provides an opportunity to examine whether climate variability interacts with forestry treatments, in a predictable manner. Here we use data from the HJ Andrews Experimental Forest, Oregon, USA, to examine the impact of the El Niño-Southern Oscillation (ENSO) on streamflow linked to forest harvesting. Our results show that the contrast between El Niño and La Niña events is so large that, whatever the state of the treated watershed in terms of re-growth of the forest canopy, extreme climatic variability related to ENSO remains the more dominant driver of streamflow response at this location. Improvements in forecasting inter-annual variation in climate might be used to minimise the impact of forestry treatments on streamflow by avoiding initial operations in La Niña years.

Introduction

Paired watershed[1] experiments have been used in forest hydrology for over one hundred years (Engler, 1919; Bates 1921; Bates and Henry, 1928) and such studies have been reviewed extensively (Bosch and Hewlett, 1982; Best et al, 2003; Andréassian, 2004). The method was refined at the Coweeta Hydrological Laboratory from the 1930s onwards (for review see Swank and Crossley, 1988) and has remained essentially unchanged since it was first formulated: identify two contiguous watersheds, as similar as possible in terms of climate, soil, topography and forest cover; monitor meteorological conditions and stream flow for several years under these similar conditions of forest cover. Then, alter one of the watersheds in terms its forest cover and continue the measurements as before, until the effects of the land use change upon the timing and amount of streamflow and the flux of particulate and dissolved material carried by the streams has been determined by comparison of hydrological records from the two watersheds. Such an approach can be applied to afforestation, deforestation, regrowth and forest conversion (Best et al., 2003).

Whilst some studies have pointed out weaknesses in the before-after statistical treatment approach for paired watershed studies (e.g. Alila et al., 2009) and offered alternative model-based approaches (Seibert and McDonnell, 2010), little work has examined the effects of climate variability on streamflow in the context of the paired watershed approach. The paired watershed experimental design 'controls' for climate variability but within this control, climate variability may interact with forestry treatments. Here, we examine the effect of forest harvesting on streamflow using paired watershed data from the H.J. Andrews Experimental Forest, Oregon, USA to test the hypothesis that climate can be ignored. Links between the El Niño-Southern Oscillation (ENSO) and significant inter-annual variability in streamflow in the Cascade Mountains of north-western USA are well known (Piechota et al, 1997; Hamlet and Lettenmeier, 2007; Abatzoglou et al., 2014). In general, the warm phase (El Niño) of the ENSO cycle results in below-average streamflow in the Cascades; and *vice versa* in La Niña events - "in general" because there are different types of El Niño events (Fu et al, 1986) and so precipitation and streamflow responses may vary for a given type of event. For both El Niño and La Niña events, precipitation and streamflow anomalies are amplified on the high-precipitation, windward side of the Cascade Mountains (Leung et al., 2003), the location of our study site.

Using paired watershed analysis from the HJ Andrews Experimental Forest, Oregon, USA, we ask the question: how does post-treatment runoff vary depending on inter-annual climate variation? The significance of improved understanding of the influence of climate for landscape management is also briefly discussed.

Methods

We examined streamflow records for two first-order watersheds (WS) in the HJ Andrews Experimental Forest, WS1 and WS2. In both cases, daily mean flows (mm) are available from 1 October 1952 to 30 September 2011; the water year (WY) is taken to begin on 1 October so the records cover 59 complete WYs. In addition to runoff totals, flow duration curve analysis and Q-frequency analysis was used (Q1, Q5, Q10, Q90; where, for example, Q10 is the discharge exceeded on 10% of days for the period in question). The paired watersheds WS1 and WS2 have been described in many publications (e.g. Jones and Grant, 1996) so only a brief summary is provided here. WS1 and WS2 are low-elevation watersheds (460-990 m and 530-1070 m above sea level respectively: Jones and Grant, 1996). Mean annual precipitation (1958-2012) at the nearby CS2MET rain gauge is 2259 mm. Over 90% of the annual precipitation falls between October and May; some falls as snow. Results are confined here to the extended winter November to May (n-m) inclusive since over 90% of runoff occurs during this time. Given a control period of nine WYs, we have likewise divided the treatment period (TP) into five nine-year periods to enable comparison (Table1).

WS1 was 100% clear-cut from 1962 to 1966 and broadcast burned in 1967. The adjacent WS2 was used as a control watershed. Before treatment, the vegetation of both watersheds consisted of old-growth Douglas fir (*Pseudotsuga menziesii*) with western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) in closed-canopy stands ranging from 150 to 500 years in age. Data from the control period (data from the November-May period for WYs 1953-1961 inclusive) were used to predict WS1 response in the post-treatment period (Burt and Swank, 1992): total streamflow (Q_{n-m}) and number of Q10 days ($Q10_{n-m}$). Although the sample size is necessarily limited in each case (n=9), the regression equations were highly significant in both cases: $R^2 = 91\%$, $p < 0.0001$. Examination of flow duration curves (FDCs) also followed the approach of Burt and Swank (1992), allowing the influences of climate and land use to be compared over the study period. Flow data were divided into the control period (WYs 1953 – 1961) and five periods post-treatment (all nine years long to match the control period).

We used sea-surface temperature anomaly data for the NINO34 region (120°W – 170°W, 5°S – 5°N) of the equatorial Pacific Ocean (Kaplan et al., 1998) to characterise ocean-atmosphere conditions in the Pacific, for which large positive values represent El Niño events and large negative values signify La Niña conditions. An extended series of SST anomaly data for equatorial regions of the Pacific Ocean based on Kaplan et al (1998) is available at: http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.

Results and discussion

Changes in water yield

Figure 1 shows the difference between predicted and actual values for Q_{n-m} and $Q10_{n-m}$. The influence of clear-cutting on streamflow in WS1 is unambiguous (Table 1, Figure 1). In the control period, WS2 was wetter in every year except one; after clear-cutting, this has happened only twice in 45 years (1997, 2007). Despite the sustained increase in streamflow following clear-cutting at WS1, the response of both watersheds is very similar, dominated by rainfall inputs in both cases as expected. Annually, 59% of rainfall was converted into runoff at WS1 and 56% at WS2 and there were highly significant correlations between P_{n-m} and Q_{n-m} in both cases (WS1: R^2 = 0.93, WS2: R^2 = 0.94) as expected.

In Treatment Period 1, Q_{n-m} from WS1 increased by 16% (Table 1). Total streamflow from WS1 was 300 mm greater than predicted at the start of the treatment period (Figure 1a). Thereafter, there was a steady and highly significant decline (p<<0.0001) but the predicted annual difference is still about 100 mm today and it may be several decades before total flow again becomes greater in WS2, as it was during the control period. It is apparent therefore that a 40-year-old forest still loses less water by evaporation and more in runoff than an old-growth stand. The pattern for predicted difference in number of $Q10_{n-m}$ events is more variable but there is nevertheless a clear pattern in the post-treatment period (Figure 1b): an initial increase of about 10 $Q10_{n-m}$ days per year and thereafter a steady, statistically significant (p=0.038) decline. However, when inter-annual climate variability is taken into account, some interesting and potentially important effects appear: streamflow response is not solely determined by the impact of forestry operations. This has been overlooked because the paired watershed experimental design, which estimates the effect as the difference between treatment and control (used to estimate treatment), has removed the climate variability.

ENSO effects on flow

For both watersheds there is a significant relationship between total streamflow (Q_{n-m}) and the NINO34 index:

WS1: $Q_{n-m} = 1307 – 195.\text{NINO34}_{n-m}$, $R^2 = 0.18$, p = 0.004 (1)

WS2: $Q_{n-m} = 1214 – 200.\text{NINO34}_{n-m}$, $R^2 = 0.18$, p = 0.005 (2)

This confirms earlier research that that streamflow tends to be higher in La Niña events and lower for El Niño events. Not surprisingly, rainfall amounts are strongly correlated with ENSO conditions too. Mean rainfall for November – May is 1912 mm, averaging 1638 mm in El Niño events and 2263 mm for La Niña events. The number of days per year receiving 25 mm or more (medium and high-flow events as defined by Seibert and McDonnell, 2010) increases from 20 (El Niño) to 30 (La Niña); the mean is 24.

There is also a significant lag between ENSO conditions and streamflow response which may be helpful for forecasting purposes: Q_{n-m} in both watersheds is significantly correlated with the average NINO34 value for the previous summer, June through October ($NINO34_{j\text{-}o\text{-}1}$: i.e. the NINO34 average for the 5 months immediately preceding the November to May period):

$$WS1: Q_{n\text{-}m} = 1333 - 265.NINO34_{j\text{-}o\text{-}1},\ R^2 = 0.24,\ p = 0.0008 \qquad (3)$$

$$WS2: Q_{n\text{-}m} = 1240 - 272.NINO34_{j\text{-}o\text{-}1},\ R^2 = 0.24,\ p = 0.0009 \qquad (4)$$

This raises the possibility of flow forecasting and varying management decisions, a matter to which we return later.

Table 2 shows the influence of El Niño and La Niña events on the streamflow regime: as expected, El Niño events are drier than normal. There is lower total streamflow ($Q_{n\text{-}m}$) and fewer high-flow days ($Q10_{n\text{-}m}$, $Q5_{n\text{-}m}$, $Q1_{n\text{-}m}$); low flows ($Q90_{n\text{-}m}$) are not affected in winter, although they are in summer (results not shown). Table 2 shows that, averaged over the entire treatment period, both watersheds have very similar results, emphasising the way in which hydroclimatic variability, as influenced by ENSO, introduces a source of variability of equivalent magnitude to that provided by land use change. Table 3 presents $Q10_{n\text{-}m}$ data for the control and post-treatment periods. In all cases except the control period, the number of $Q10_{n\text{-}m}$ days in an El Niño event is below the mean; the 1958 (control period) the El Niño was anomalously wet which accounts for above-average $Q10_{n\text{-}m}$ days. The large contrast between El Niño and La Niña events is once again very clear, indicating that, whatever the condition of the treated watershed in terms of re-growth of the forest canopy climatic variations related to ENSO remain the more dominant driver of streamflow variability at this location.

Flow duration curve analysis

Figure 2 shows FDCs for the control period and all post-treatment periods. During the control period, WS2 streamflow exceeds WS1 except for the highest flows (Q3 - Q1) where WS1 has marginally higher runoff for a given flow frequency. In the first treatment period, WS1 exceeds WS2 at above-average flow frequencies and at the lowest flows, showing that the additional runoff because of clear-cutting affects both stormflow and baseflow. By the fifth period, WS2 exceeds WS1 across most of the flow range, but WS1 still has higher numbers of high-discharge, low-frequency flows.

Figure 3 includes FDCs for the largest El Niño and La Niña events in each period (as measured by the NINO34 index). In the control period, there is limited contrast between the two years (El Niño: 1958, La Niña: 1956) because this particular El Niño was quite wet so runoff remained quite high. The FDC for WS2 is only a little above that for WS1 in the La Niña year but the difference between watersheds is much greater in the drier El Niño year. In the control period therefore, WS2 always produced more runoff, especially in drier years.

In the first post-treatment period, El Niño and La Niña years are very different. For the El Niño year (1973); the WS1 curve is entirely above that for WS2, as would be expected immediately after clear-cutting. However, for the La Niña year (1974), the very wet conditions seem to generate particularly high streamflow from WS2 which has higher low flows and only falls below WS1 for the highest flows. The same patterns are seen in Period 2. For later periods, FDCs for both watersheds are very similar but low flows in El Niño years are once again higher in WS2. The differences between El Niño and La Niña years are least in Period 4, probably because again the El Niño year was relatively wet. In the other periods, there is a clear difference between FDCs in El Niño and La Niña years; both watersheds have a very similar response for a given year.

It is self-evident that runoff will be higher in wet years, and *vice versa*. What is apparent here is that high-frequency climate variation obscures the emerging pattern associated regrowth following clear-cutting. Unlike the results presented by Burt and Swank (1992), where clear differences between treatment and control FDCs were sustained throughout the treatment period, here the main contrast in FDCs is between wet and dry years, not between treatment and control. True, the expected pattern of change with forest regrowth is observed: the difference between expected and actual Qn-m from WS1 falls by about 150 mm over 40 years (Figure 1a); at the same time the number of Q10 events is halved. Nevertheless, significant short-term climatic variability imparts considerable noise to the hydrological record and obscures the longer-term trend driven by land-use change. Moreover, the two watersheds appeared to behave somewhat differently in wet and dry years, at least in treatment periods 1 and 2 (Figure 3) with relatively higher flows from WS2 in wet years. Given our improved knowledge of climate variability and its potential to produce differential effects on streamflow in control vs. treated watersheds, the control period in a paired watershed experiment should be long enough to capture this variability.

A control out of control?

Table 1 shows that the control period had the highest runoff total for WS2 but there are no significant trends over time for precipitation (P), streamflow (Q) or temperature (results not shown). What is significant is an increase in the difference between P and Q (P – Q : $r = 0.37$, $p = 0.005$, $n = 55$). This suggests an increase in evaporation for the November to May period, which could be the results of a combination of combined changes in temperature and wind speed. Further work is needed on this intriguing finding, which is beyond the scope of this discussion, but it suggests a possible non-stationarity in the control. Various alternative hypotheses for the apparent long-term trend in declining Q/P at WS2 include release of understory hemlock due to cumulative mortality of the 500-yr old over-storey Douglas fir or changing temperature. There is no long-term trend in measured (i.e. near-ground-level) temperature but in a stepwise multiple regression analysis of the long-term P – Q trend, without itself being a significant addition, temperature does increase the variance explained from 14% to 21%. If temperature change were involved, this might be evident from above-canopy measurements but unfortunately we do not have records of air temperature trends at the top of the canopy (which is 80-90 m tall).

This apart, the control period is notable for its lack of extreme ENSO conditions, compared to all but Treatment Period 5. This means that, with hindsight, the control period did not include the very dry or very wet conditions usually associated with El Niño and La Niña events respectively, meaning that the full range of possible climatic variability was not experienced during the control period. Nine years is a typical – even generous - length of control period but not long enough perhaps?

Implications

Three implications can be drawn from this analysis of relevance to paired watershed experiments and the management of water resources in forested watersheds:

1. Wherever subtle processes are embedded within highly variable systems, a weak signal cannot be extracted from a noisy background without a long record (Burt, 1994). With respect to paired watershed experiments, this emphasises the need for continued monitoring over long (treatment) periods, especially at locations like H J Andrews where short-term climatic variation is significant compared to any long-term trend.
2. It follows that, if the study site is in a region affected by extreme climatic variation, then the control period must be long enough to capture this variability. Otherwise, the extreme differences in runoff, for example between El Niño and La Niña conditions, might not be factored into calculations about available water resources. The expected increase in water yield would no doubt happen after deforestation but there might well be more inter-annual variability than expected.
3. Provided that there is some leeway over and above economic considerations such as the price of timber, then the ability to forecast rainfall and streamflow might help avoid excessive runoff and erosion by delaying harvesting operations for a year. Looking at correlations between NINO34 and streamflow the following winter, the earliest month to provide a significant correlation is June ($R^2 = 0.1329$, $p = 0.016$); however, despite being statistically significant, the level of variance explained is low and this would be a weak basis for forecasting. Nevertheless, since the June NINO34 index value would be available mid-July, this suggests that, if clear-cutting could be delayed until August, it would be possible to forecast whether the following winter is likely to be very wet (La Niña) or not, so avoiding the possibility of high surface runoff on unprotected soil. However, these comments need placing in context: the treatment in WS1 involved clear-cutting old-growth (150-500 year-old) forests; this has not been legal for 20 years in the Pacific Northwest. The only places where clear-cutting is being done in the Pacific Northwest are private land on a 70-year rotation. Thus, our comment about forecasting might be relevant generally but not at H J Andrews specifically.

Additionally, there are other practical issues related to harvest planning months or years into the future, including staffing and machinery. It is clear therefore that much more reliable forecasting methods will be needed before environmental impact can take priority over economic considerations.

Concluding comments

While it is intuitive that a wet year will have more runoff and sediment transport than a dry year, the results demonstrate that, whatever the condition of the treated watershed in terms of re-growth of the forest canopy, extreme climatic variations related to ENSO remain the more dominant driver of streamflow variability at this location. The important finding that streamflow response in both watersheds is significantly correlated with the average NINO34 value for the previous summer suggests the possibility of flow forecasting and varying management decision making.

Whilst the paired-watershed approach is not compromised via our observations (although we do note the arguments made by Alila et al., 2009 that may compromise the paired watershed approach in other ways), this study suggests that greater caution is needed than previously realised in relation to the length of the initial “control” period. On the other hand, knowledge of potential climatic impacts may eventually benefit management decisions, avoiding particularly problematic La Niña-impacted weather conditions. The ability to reliably forecast streamflow could help avoid excessive impact by delaying harvesting operations.

The findings here demonstrate the need for long-term environmental monitoring to enhance decision making and planning. Multi-decadal data sets are needed to better understand forestry management and watershed impacts. Understanding the response of runoff to climate and forestry management is critical but there may be unforeseen and unknown ecohydrological trends and effects that may only be revealed at long time scales. The findings here highlight the benefit of such observations.

Finally, our analysis reinforces the emerging consensus that inter-annual climate variability is high relative to long-term trends in climate (see Abatzoglou et al., 2013); it makes sense that inter-annual streamflow variability will be high, too. The Andrews Forest appears to be located at a latitude where it experiences climate variability associated with both the equatorial Pacific and the northern Pacific; future research might therefore explore the influence of indices in addition to ENSO (e.g. the Pacific Decadal Oscillation) to better explain streamflow variability. It is also the case that long-term climate change-related trends are evident in streamflow records for much of the Pacific Northwest, namely increases in spring flow and declining late summer flow (Hatcher and Jones, 2013; Dettinger, 2014). In relation to controls on orographic rainfall, Luce et al (2013) identified links between atmospheric circulation and precipitation totals in the Pacific Northwest similar to those identified by Burt and Howden (2013) for upland Britain and the Pacific Northwest. This raises the question as to whether significant climate variability effects on streamflow might also be apparent at other, mid-latitude, west-coast locations, such as Britain or Chile,

Acknowledgements

The authors would like to thank two anonymous referees for their comments on the original manuscript. This research was begun when TPB and GRH were Visiting Fellows at the Institute for Water & Watersheds, College of Forestry, Oregon State University. Data sets were provided by the HJ Andrews Experimental Forest research program, funded by the National Science Foundation's Long-Term Ecological Research Program (DEB 0823380), US Forest Service Pacific Northwest Research Station, and Oregon State University. Grateful thanks to Don Henshaw for updates.

References

Alila Y, Kuras PK, Schnorbus M, Hudson R. 2009. Forests and floods: A new paradigm sheds light on age-old controversies. *Water Resources Research* **45**: W08416, doi:10.1029/2008WR007207.

Abatzoglou JT, Rupp DE, Mote PW. 2014. Seasonal Climate Variability and Change in the Pacific Northwest of the United States. *Journal of Climate* 27 (5), 2125-2142.

Andréassian V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology* 291: 1-27.

Bates CG. 1921. First results in the streamflow experiment Wagon Wheel Gap, Colorado. *Journal of Forestry* **19**: 402-408.

Bates CG, Henry AJ. 1928. Second phase of streamflow experiment at Wagon Wheel Gap, Colorado. *Monthly Weather Review* **56** (3): 79-98.

Best A, Zhang L, McMahon T, Western A, Vertessy R. 2003. A critical review of paired watershed studies with reference to seasonal flows and climatic variability. CSIRO Land and Water Technical Report 25/03. Murray-Darling Basin Commission, Canberra.

Bosch JM, Hewlett JD. 1982. A review of watershed experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**: 3-23.

Burt TP. 1994. Long-term study of the natural environment: perceptive science or mindless monitoring? *Progress in Physical Geography* **18**: 475-496.

Burt TP, Swank WT. 1992. Flow frequency responses to hardwood-to-grass conversion and subsequent succession. *Hydrological Processes* **6:** 179-188.

Burt TP, Howden NJK. 2013. North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. *Water Resources Research* **49**: 3504-3515, doi: 10.1002/wrcr.20297.

Dettinger M. 2014. Impacts in the third dimension. *Nature Geoscience* **7**: 166-167.

Engler A. 1919. Experiments showing the effect of forests on the height of streams. Mitteilungen der Schwelzerischen Centralanstalt fur das Forstliche Versuchswesen. XII, Zurich.

Fu C, Diaz HF, Fletcher JO. 1986. Characteristics of the response of sea surface temperature in the Central Pacific associated with warm episodes of the Southern Oscillation. *Monthly Weather Review* **114**: 1716-1738.

Hamlet AF, Lettenmaier DP. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. *Water Resources Research* **43**: W06427, doi:10.1029/2006WR05099.

Hatcher KL, Jones JA. 2013. Climate and streamflow trends in the Columbia rover basin: evidence for ecological and engineering resilience to climate change. *Atmosphere-Ocean*. DOI:10.1080/07055900.2013.808167.

Jones JA, Grant GE. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western cascades, Oregon. *Water Resources Research* **32**(4): 959-974.

Kaplan A, Cane MA, Kushnir Y, Clemet AC. Blumenthal MB, Rajagoplana B. 1998. Analyses of global sea surface temperature 1856-1991. *Journal of Geophysical Research* **103** (C9): 18,567-18,589.

Leung LR, Qian Y, Bian X, Hunt A. 2003. Hydroclimate of the western United States based on observations and regional climate simulation of 1981–2000. Part II: mesoscale ENSO anomalies. *Journal of Climate* **16:** 1912-1928.

Luce CH, Abatzoglou JT, Holden ZA. 2013. The missing mountain water: slower westerlies decrease orographic enhancement in the Pacific Northwest USA. *Science* **342**: 1360-1364. DOI: 10.1126/science.1242335.

Piechota TC, Dracup JA, Fovell RG. 1997. Western US streamflow and atmospheric circulation patterns during El Niño-Southern Oscillation. *Journal of Hydrology* **201**: 249-271 (1997).

Seibert J, McDonnell JJ. 2010. Land-cover impacts on streamflow: a change-detection modelling approach that incorporates parameter uncertainty. *Hydrological Sciences Journal* **55**(3): 316-332, (2010).

Swank WT, Crossley DA, (editors). 1988. Forest hydrology and ecology at Coweeta. *Ecological Studies* **66**. Springer-Verlag, New York, 469pp.

Walker GT. (1924). Correlations in seasonal variations of weather IX. *Memoirs of the India Meteorological Department* **24** (9): 275-332.

Footnote

1. Given the location of the study area and names used at the H J Andrews Experimental Forest, we use here the American term “watershed” to denote the drainage basin or watershed.

Figure captions

Figure 1. The difference between actual and predicted values for WS1 for (a) streamflow (mm) and (b) the number of Q10 days. Both plots cover the extended winter period November through May.

Figure 2. Flow duration curves for the control period and five treatment periods. WS1 is shown in blue and WS2 in red.

Figure 3. Flow duration curves for the two watersheds for the control period and five treatment periods. The years selected had the largest values of the NINO34 index within each period: positive for El Niño (red lines) and negative for La Niña (blue lines). For each pair of lines, WS1 is the darker colour and WS2 the paler colour.

Table captions

Table 1. Summary data for the control and five treatment periods. All results are for the extended winter November to May. Total runoff (TOT) is in millimetres. Values listed for the NINO34 index are the maximum and minimum November to May (n-m) average during each period. Dates refer to water years.

Table 2. Mean values for a range of flow statistics at WS1 and WS2, for the treatment period (1967-2012) and for El Niño and La Niña events. All results are for the November to May (n-m) extended winter, except that summer low flow data ($Q90_{j\text{-}o}$) are included in the right-hand column. Variables are defined in the text. Values of the NINO34 index greater than one standard deviation either side of the mean were used to identify El Niño and La Niña events. Note that this yields fewer “ENSO” periods than listed by Leung et al (2003). 1983 was an exceptionally wet El Niño; following Piechota et al (1997), this was excluded from the calculations.

Table 3. Number of days November to May when streamflow exceeded $Q10_{n\text{-}m}$. Given the small number of El Niño and La Niña events in each period, results from specific years rather than mean values are given. The years selected had the largest values of the NINO34 index within each period: positive for El Niño and negative for La Niña. Again, 1983 is excluded from the analysis.